THERMOELECTRIC GENERATION SYSTEM UTILIZING A PRINTED-CIRCUIT THERMOPILE

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TECHNICAL FIELD OF THE INVENTION

[0001] The present invention relates to the field of electrical generation. More specifically, the present invention relates to the field of electrical generation utilizing the Seebeck effect.

BACKGROUND OF THE INVENTION

[0002] A majority of electrical generation systems conventionally use mechanical energy to drive a magnetic generator and produce the desired electrical energy. This mechanical energy may be natural or produced, but in all case requires conversion prior to use. This conversion of energy results in a marked loss of efficiency in such a system.

[0003] In thermo-mechanical generation systems, thermal energy is used to produce steam. The steam in turn drives a turbine to produce rotary mechanical energy. The rotary mechanical energy is then used to drive a conventional magnetic generator to produce the electricity. Since each step in this process has losses, the resultant electrical energy represents only a fraction of the applied thermal energy. The thermal energy required of a thermo-mechanical generation system may be produced by the burning of a fossil or nuclear fuel, obtained from the concentration of solar energy, or obtained directly from geothermal activity. The source of the thermal energy for a thermo-mechanical generation system is irrelevant to the generation process.

[0004] In "natural" mechanical generation systems, a substantially linear or reciprocation mechanical energy is applied to a turbine to produce the requisite rotary mechanical energy to drive the conventional magnetic generator. Examples of

"natural" mechanical generation systems are hydrodynamic, wind, and tidal systems.

[0005] A problem with all such mechanical generation systems is that they are mechanical and complex. That is, they contain moving parts and often require a sophisticated infrastructure for operation. With a conventional fossil-fuel generation system, the generation system comprises a sophisticated concatenation of mechanical systems is required. In addition, a highly complex infrastructure for the acquisition and shipment of the fossil fuel, and of the disposal of the resultant "ash," is required above and beyond the generation system itself.

[0006] Solar photovoltaic generation systems have no moving parts and therefore present a viable alternative source of electrical energy. Unfortunately, solar systems of all types are subject to diurnal, climatological, and meteorological limitations. Because of this, solar system typically have electrochemical storage devices (e.g., batteries) to compensate for the day-night cycle, the changing of the seasons, and adverse weather. These devices, while not having the complex moving parts of the mechanical systems, have their own limitations and problems.

[0007] Ideally, an electrical generation system should be simple in structure, have no moving parts, and be immune to diurnal, climatological, and meteorological effects.

SUMMARY OF THE INVENTION

[0008] Accordingly, it is an advantage of the present invention that a thermoelectric generation system utilizing a printed-circuit thermopile is provided.

[0009] It is another advantage of the present invention that a thermoelectric generation system is provided that is immune to diurnal, climatological, and meteorological effects.

[0010] It is another advantage of the present invention that a thermoelectric generation system is provided that has no moving parts.

[0011] It is another advantage of the present invention that a thermoelectric generation system is provided that is readily adaptable to variant energy needs.

[0012] The above and other advantages of the present invention are carried out in one form by a printed-circuit thermopile formed of a printed-circuit substrate having a first surface and a second surface, and having a first thermal portion and a second thermal portion, a plurality of first traces, wherein each of the first traces is formed of a first metal and extends between the first and second thermal portions upon the first surface, a plurality of second traces, wherein each of the second traces is formed of a second metal and extends between the first and second thermal portions upon the second surface, a plurality of first junctions, wherein each of the first junctions couples one of the first traces with one of the second traces in the first thermal portion, and a plurality of second junctions, wherein each of the second junctions couples one of the first traces with one of the second traces in the second thermal portion, and wherein each of the second junctions is in series with one of the first junctions.

[0013] The above and other advantages of the present invention are carried out in one form by a thermoelectric generation system configured to provide electrical energy at a predetermined voltage and current, and incorporating a plurality of printed-circuit thermopiles and a backplane coupled to and configured to electrically connect the thermopiles to provide the electrical energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] A more complete understanding of the present invention may be derived by referring to the detailed description

and claims when considered in connection with the Figures, wherein like reference numbers refer to similar items throughout the Figures, and:

[0015] FIG. 1 shows a schematic view of a closed-loop type-T thermocouple;

[0016] FIG. 2 shows a chart depicting a temperature versus output curve for a type-T thermocouple;

[0017] FIG. 3 shows a schematic view of a static model of the closed-loop thermocouple of FIG. 1;

[0018] FIG. 4 shows a schematic view of an open-loop type-T thermocouple;

[0019] FIG. 5 shows a schematic view of a static model of a the open-loop thermocouple of FIG. 3 under load;

[0020] FIG. 6 shows a schematic view of a series thermopile in accordance with a preferred embodiment of the present invention;

[0021] FIG. 7 shows a schematic view of a parallel thermopile in accordance with a preferred embodiment of the present invention;

[0022] FIG. 8 shows a schematic view depicting a composite thermopile in accordance with a preferred embodiment of the present invention;

[0023] FIG. 9 shows a schematic view of an exemplary thermopile in accordance with a preferred embodiment of the present invention;

[0024] FIG. 10 shows a front view of a printed-circuit thermopile in accordance with a preferred embodiment of the present invention;

[0025] FIG. 11 shows an end view of a plurality of printed-circuit thermopiles arranged as a thermoelectric generation system in accordance with a preferred embodiment of the present invention;

[0026] FIG. 12 shows a cross-sectional view of the printed-circuit thermopile of FIG. 10 taken at line 12-12 and demonstrating an overlap junction in accordance with a first preferred embodiment of the present invention;

[0027] FIG. 13 shows a cross-sectional view of the printed-circuit thermopile of FIG. 10 taken at line 12-12 and demonstrating a filled junction in accordance with a second preferred embodiment of the present invention;

[0028] FIG. 14 shows a cross-sectional view of the printed-circuit thermopile of FIG. 10 taken at line 12-12 and demonstrating a pin junction in accordance with a third preferred embodiment of the present invention; and

[0029] FIG. 15 shows a cross-sectional view of the printed-circuit thermopile of FIG. 10 taken at line 12-12 and demonstrating a heat-sink junction in accordance with a fourth preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0030] FIG. 1 shows a schematic view of a type-T closed-loop thermocouple $TC_{[C]}$. In its simplest form, a thermocouple TC is made up of a first conductor 20 formed of a first metal and a second conductor 22 formed of a second, dissimilar metal. First and second conductors 20 and 22 are joined at one end to form a first junction J_1, and at the other end to form a second junction J_2. Thermocouple TC therefore forms a closed loop, i.e., is a closed-loop thermocouple $TC_{[C]}$.

[0031] In the preferred embodiment of FIG. 1, thermocouple TC is a type-T or copper-constantan thermocouple. That is, first conductor 20 is formed of copper (*Cu*), and second conductor 22 is formed of the copper-nickel alloy constantan (*Cu/Ni*). Those skilled in the art will appreciate, however, that a copper-constantan thermocouple is not a requirement of the present invention, and that other materials may be used for either first

or second conductor 20 or 22 without departing from the spirit of the present invention.

[0032] When first junction J_1 is at a first temperature T_1 and second junction J_2 is at a second temperature T_2, then a voltage E_{TC} is generated between first and second junctions J_1 and J_2. This generation of voltage E_{TC} is known as the Seebeck effect. The value of voltage E_{TC} is a function of:

$$T_{TC} = |T_1 - T_2|, \text{ and} \tag{1}$$

$$E_{TC} = S \times T_{TC}, \tag{2}$$

where:

E_{TC} is the differential temperature across thermocouple TC; and

S is the Seebeck coefficient for thermocouple TC.

[0033] FIG. 2 shows a chart depicting a temperature versus output curve for thermocouple TC. The following discussion refers to FIGs. 1 and 2.

[0034] Seebeek coefficient S for a given thermocouple type changes with temperature. However, for a given thermocouple TC, coefficient S may be approximately linear for a given differential temperature T_{TC}.

[0035] In FIG. 2 it may be seen that, when first junction J_1 is at a first temperature T_1 of 0°C and second junction J_2 is at a second temperature T_2 of 100°C, a type-T thermocouple TC has a differential temperature T_{TC} of 100°C and produces a voltage E_{TC} of 4.279 mV. Over this range, therefore, coefficient S is ≈42.79 µV/°C.

[0036] In the preferred embodiment, thermocouple TC is a type-T copper-constantan thermocouple. A type-T thermocouple is formed of copper and constantan. Copper is an elemental metal having a low electrical resistivity. Constantan (a.k.a. 55/45 constantan, ferry, hecnum, and telconstan) is an alloy of 53.8%

copper, 44.2% nickel, 1.5% manganese, and 0.5% iron, having a high electrical resistance and a low temperature coefficient. Copper and constantan have the relevant characteristics depicted in table 1:

Property @ 20°C	Copper	Constantan	Units
Temperature Coefficient	+0.0043	±0.00002	K^{-1}
Electrical Resistivity	1.69	52.0	μΩ cm
	10.164	312.75	Ω/CMF
Density	8.96	8.9	g cm^{-3}
Coefficient of Thermal Expansion	17.0	14.9	$\times 10^{-6}$ K^{-1}
Thermal Conductivity	401	19.5	W m^{-1} K^{-1}

TABLE 1—Characteristics of Copper and Constantan

[0037] With the understanding that other type of thermocouples and/or other temperatures may be used, this discussion will hereinafter assume for the sake of simplicity that thermocouple TC is a type-T copper-constantan thermocouple, that first conductor 20 is formed of copper, that second conductor 22 is formed of constantan, that first junction J_1 is at a first temperature T_1 of 0°C, that second junction J_2 is at a second temperature T_2 of 100°C, that differential (thermocouple temperature T_{TC} is 100°C, and that thermocouple voltage E_{TC} is 4.279 mV.

[0038] FIG. 3 shows a schematic view of a static model of closed-loop thermocouple $TC_{[C]}$. The following discussion refers to FIGs. 1 and 3.

[0039] Since thermocouple $TC_{[C]}$ is a closed loop with voltage E_{TC} expressed between junctions J_1 and J_2, thermocouple $TC_{[C]}$ represents a closed circuit. Voltage E_{TC} causes a current I_{TC} to flow through this closed circuit, i.e., through thermocouple $TC_{[C]}$. By Ohm's law:

$$I_{TC} = \frac{E_{TC}}{R_{TC}} = \frac{E_{TC}}{R_{Cu} + R_{Cu/Ni}}, \quad (3)$$

where:

R_{TC} is the resistance of thermocouple $TC_{[C]}$;

R_{Cu} is the resistance of copper conductor 20, and

$R_{Cu/Ni}$ is the resistance of constantan conductor 22.

[0040] As discussed hereinbefore, copper has a resistivity of 1.69 μΩ cm (i.e., 1.69×10^{-6} ohms for a conductor having a cross-section area of 1 square centimeter and a length of 1 centimeter). This equates to 10.164 Ω/CMF (i.e., 10.164 ohms for a conductor having a cross-sectional area of 1 circular mil and a length of 1 foot). Similarly, constantan has a resistivity of 52.0 μΩ cm or 312.75 Ω/CMF. This means that constantan has approximately 30.8 times the resistivity of copper.

[0041] FIG. 4 shows a schematic view of an open-loop type-T thermocouple $TC_{[O]}$, and FIG. 5 shows a schematic view of a static model of an open-loop thermocouple $TC_{[O]}$ under load. The following discussion refers to FIGs. 1, 2, 4, and 5.

[0042] A closed-loop thermocouple $TC_{[C]}$ serves no purpose (other than an instructional purpose) because both voltage E_{TC} and current I_{TC} are isolated from the real world. However, if either of first or second conductors 20 or 22 is opened, closed-loop thermocouple $TC_{[C]}$ becomes open-loop thermocouple $TC_{[O]}$.

[0043] Open-loop thermocouple $TC_{[O]}$ represents an open circuit. There is, therefore, no current I_{TC} flowing through open-loop thermocouple $TC_{[O]}$ (as depicted in FIG. 4). Since there is no current I_{TC}, voltage E_{TC} is present at the ends of the opened conductor. A theoretical infinite-resistance voltage-measuring device (not shown) could be coupled to the opened ends and measure voltage E_{TC}. Having an infinite resistance, the voltage-measuring device does not close the circuit through thermocouple $TC_{[O]}$ and current I_{TC} remains at zero. The voltage-measuring device could then determine voltage E_{TC} with great accuracy. The Seebeck effect for specific thermocouples is well known.

Therefore, differential thermocouple temperature T_{TC} may also be determined with great accuracy. If one of the junction temperatures T_1 or T_2 is known, then the other may be determined. For example, if temperature T_1 of junction J_1 is known to be 0°C and thermocouple voltage E_{TC} is measured to be 4.279 mV, then temperature T_2 of junction J_2 must be 100°C. Indeed, use as a temperature-measuring device is the most common conventional use of thermocouple TC.

[0044] Those skilled in the art will appreciate that an infinite-resistance voltage measuring device does not exist, and that, in practice, the voltage measuring device must have some resistance. Since it is desirable that the measuring device measure voltage E_{TC} as accurately as possible, it is desirable that the resistance of the measuring device, a load resistance R_L in FIG. 5, be as high as possible. A current I_L through a loaded thermocouple $TC_{[L]}$ would then be a function of thermocouple resistance R_{TC} in series with load resistance R_L:

$$I_L = \frac{E_{TC}}{R_{TC} + R_L}. \qquad (4)$$

[0045] If load resistance R_L is very much (e.g., several orders of magnitude) higher than thermocouple resistance R_{TC}, then thermocouple resistance R_{TC} is negligible and current I_L becomes substantially a function of load resistance R_L:

$$I_L = \frac{E_{TC}}{R_{TC} + R_L} \cong \frac{E_{TC}}{R_L}. \qquad (5)$$

[0046] Voltage E_{TC} is proportionately expressed across thermocouple resistance R_{TC} and load resistance R_L in series. By Kirchhoff's law, we know:

$$E_{TC} = E_{TR} + E_L, \qquad (6)$$

where:

E_{TR} is the voltage expressed across thermocouple resistance R_{TC}, and

E_L is the voltage expressed across load resistance R_L.

[0047] Since load resistance R_L is very much greater than thermocouple resistance R_{TC}, then thermocouple resistance R_{TC} is negligible:

$$E_{TC} = E_{TR} + E_L \cong E_L \, , \tag{7}$$

[0048] In the case of use as a measuring device, therefore, it is desirable to have current I_L through loaded thermocouple $TC_{[L]}$ as low as possible. When thermocouple TC is to be used as an electrical generation device, however, it is desirable that the energy generated be as high as possible. This necessitates that, for a give voltage E_{TC}, current I_{TC} be as high as possible.

[0049] For a given loaded thermocouple $TC_{[L]}$, current I_L has a maximum value when load resistance R_L is zero, i.e., when thermocouple TC is a closed-loop thermocouple $TC_{[C]}$. It is therefore desirable that load resistance R_L be very much (e.g., several orders of magnitude) lower than thermocouple resistance R_{TC}. In this case, load resistance R_L becomes negligible and current I_L becomes substantially a function of thermocouple resistance R_{TC}:

$$I_L = \frac{E_{TC}}{R_{TC} + R_L} \cong \frac{E_{TC}}{R_{TC}} = I_{TC} \, . \tag{8}$$

[0050] For the sake of simplicity, the remainder of this discussion presumes that all thermocouples TC are type-T thermocouples having substantially identical resistances R_{TC}, that all temperatures T_1 are substantially identical, that all differential thermocouple temperatures T_{TC} are substantially identical, that all thermocouple voltages E_{TC} are substantially identical, and that all thermocouple zero-load currents I_{TC} are substantially identical. Furthermore, it is assumed that all load resistances R_L for any thermocouple TC or any combination of

thermocouples TC is substantially zero. Those skilled in the art will appreciate that these conventions are exemplary only, and have no bearing in reality.

[0051] FIGs. 6, 7, and 8 show schematic views of thermopiles in accordance with a preferred embodiment of the present invention, where FIG. 6 depicts a series thermopile $TP_{[S]}$, FIG. 7 depicts a parallel thermopile $TP_{[P]}$, and FIG. 8 depicts a composite thermopile (thermoarray) TA. The following discussion refers to FIGs. 4 through 8.

[0052] Thermocouples TC may be concatenated to form a thermopile TP. FIG. 6 depicts N thermocouples $TC_{(n)}$ connected in series to form a series thermopile $TP_{[S]}$. Since thermocouples $TC_{(1)}$ through $TC_{(N)}$ are connected in series, their voltages $E_{TC(1)}$ through $E_{TC(N)}$ are summed and their currents $I_{TC(1)}$ through $I_{TC(N)}$ are not:

$$E_{TP[S]} = E_{TC(1)} + E_{TC(2)} + \cdots + E_{TC(N)}, \tag{9}$$

$$I_{TP[S]} = I_{TC(1)} = I_{TC(2)} = \cdots = I_{TC(N)}, \tag{10}$$

where:

N is an integer greater than 1,

n is an integer between 1 and N, inclusively,

$E_{TC(n)}$ is the voltage of thermocouple $TC_{(n)}$,

$I_{TC(n)}$ is the current of thermocouple $TC_{(n)}$,

$E_{TP[S]}$ is the voltage of series thermopile $TP_{[S]}$, and

$I_{TP[S]}$ is the current of series thermopile $TP_{[S]}$.

[0053] This means that for a given series thermopile $TP_{[S]}$ having N thermocouples $TC_{(n)}$, thermopile voltage $E_{TP[S]}$ is:

$$E_{TP[S]} = N \times E_{TC(n)}, \tag{11}$$

but the thermopile current $I_{TP[S]}$ is limited to the current $I_{TC(n)}$ of any one thermocouple $TC_{(n)}$.

[0054] Similarly, FIG. 7 depicts M thermocouples $TC_{(m)}$ connected in parallel to form a parallel thermopile $TP_{[P]}$. Since thermocouples $TC_{(1)}$ through $TC_{(M)}$ are connected in parallel, their

currents $I_{TC(1)}$ through $I_{TC(M)}$ are summed and their voltages $E_{TC(1)}$ through $E_{TC(M)}$ are not:

$$E_{TP[P]} = E_{TC(1)} = E_{TC(2)} = \cdots = E_{TC(M)}, \tag{12}$$

$$I_{TP[P]} = I_{TC(1)} + I_{TC(2)} + \cdots + I_{TC(M)}, \tag{13}$$

where:

M is an integer greater than 1,

m is an integer between 1 and M, inclusively,

$E_{TC(m)}$ is the voltage of thermocouple $TC_{(m)}$,

$I_{TC(m)}$ is the current of thermocouple $TC_{(m)}$,

$E_{TP[P]}$ is the voltage of parallel thermopile $TP_{[P]}$, and

$I_{TP[P]}$ is the current of parallel thermopile $TP_{[P]}$.

[0055] This means that for a given parallel thermopile $TP_{[P]}$ having M thermocouples $TC_{(m)}$, thermopile current $I_{TP[P]}$ is:

$$E_{TP[P]} = M \times E_{TC(m)}, \tag{14}$$

but the thermopile voltage $E_{TP[P]}$ is limited to the voltage $E_{TC(m)}$ of any one thermocouple $TC_{(m)}$.

[0056] FIG. 8 depicts a composite thermopile (i.e., a thermoarray) TA of M thermopiles $TP_{(m)}$ connected in parallel, where each thermopile $TP_{(m)}$ contains N thermocouples $TC_{(n,m)}$ connected in series. In this arrangement, a voltage E_{TA} of thermoarray TA is substantially equal to voltages $E_{TP(m)}$ of each thermopile $TP_{(m)}$, where voltage $E_{TP(m)}$ of each thermopile $TP_{(m)}$ is substantially equal to a sum of voltages $E_{TC(n,m)}$ of each thermocouple $TC_{(n,m)}$ in thermopile $TP_{(m)}$. Similarly, current I_{TA} of thermoarray TA is substantially equal to a sum of currents $I_{TP(m)}$ of each thermopile $TP_{(m)}$, where current $I_{TP(m)}$ of each thermopile $TP_{(m)}$ is substantially equal to current $I_{TC(n,m)}$ of each thermocouple $TC_{(n,m)}$ in thermopile $TP_{(m)}$. This may be expressed as:

$$E_{TA} = E_{TP(1)} = E_{TC(2)} = \cdots = E_{TC(M)}, \tag{15}$$

$$E_{TP(m)} = E_{TC(1,m)} + E_{TC(2,m)} + \cdots + E_{TC(N,m)}, \tag{16}$$

$$I_{TA} = I_{TP(1)} + I_{TP(2)} + \cdots + I_{TP(M)}, \text{ and} \tag{17}$$

$$I_{TP(m)} = I_{TC(1,m)} = I_{TC(2,m)} = \cdots = I_{TC(N.m)}. \tag{18}$$

[0057] This means that for a given thermoarray *TA* containing *M* thermopiles $TP_{(m)}$ in parallel, with each thermopile $TP_{(m)}$ containing *N* thermocouples $TC_{(n)}$ in series, voltage E_{TA} and current I_{TA} of thermoarray *TA* are:

$$E_{TA} = N \times E_{TC(n,m)}, \tag{19}$$

$$I_{TA} = M \times I_{TC(n,m)}. \tag{20}$$

[0058] By creating a large enough thermoarray, any desired voltage E_{TA} and current I_{TA} may be supplied. In the preferred embodiment, for example, it is desirable that ≈165 Vdc at ≈21 A (i.e., ≈3.5 kW) be generated. To produce ≈165 V requires 38,560 thermocouples *TC* connected in series. Assuming, for the sake of discussion, that each thermocouple *TC* has a resistance of 10 mΩ, then each thermocouple is capable of producing 427.9 mA. To produce ≈21 A requires 49 thermocouples *TC* in parallel. To produce ≈165 V at ≈21 A therefore requires that thermoarray *TA* be an array of 1,889,440 (38,560 × 49) thermocouples *TC*. In practice, these numbers would most likely be rounded up to 2,000,000 (40,000 × 50) thermocouples *TC*.

[0059] FIG. 9 shows a schematic view of an exemplary thermopile *TP*. FIG. 10 shows a front view of a printed-circuit (PC) thermopile 24, and FIG. 11 shows an end view of a plurality of PC thermopiles 24 arranged as a portion of a thermoelectric generation system 26 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGs. 4 and 8 through 11.

[0060] In order to make practical such a large thermoarray *TA*, it is desirable that thermopiles *TP* of very high density be realized. In the preferred embodiment, this is achieved through the use of a multiplicity of PC thermopiles 24.

[0061] Each PC thermopile 24 is desirably configured to have a high-density serial thermopile $TP_{[S]}$ arranged upon a substrate 30. Desirably, PC thermopile 24 would have traces 28 of first conductor 20 upon a first surface 32 of substrate 30, and second traces 34 of second conductor 22 upon a second surface 36 of substrate 30, with through-substrate "pads" forming the requisite junctions J_1 and J_2 for each thermocouple. This approach is demonstrated schematically in FIG. 9, which is essentially an X-ray view of the traces. In FIG. 9, all solid lines represent first traces 28 on first surface 32, all dotted lines represent second traces 34 on second surface 36, and all solid dots represent couplings 38 (discussed in more detail hereinafter) which pass through substrate 30 and form junctions J_1 and J_2.

[0062] FIG. 10 depicts first surface 32 of an exemplary PC thermopile 24. When first traces 28 on first surface 32 are coupled with second traces 34 on second surface 36 (not shown in FIG. 10) through couplings 38, 96 serially-connected thermocouples *TC* will be formed as per FIG. 9. A board connector 40 at one edge of PC thermopile 24 provides a way to connect PC thermopiles 24 together.

[0063] Those skilled in the art will appreciate that FIG. 9 is highly simplified for clarity. In practice, it would be well within the current sate of the art to produce PC thermopile 24 with 1000 thermocouples *TC*. To produce PC thermopile 24 with any given number of thermocouples *TC* does not depart from the spirit of the present invention.

[0064] FIG. 11 depicts a plurality of PC thermopiles 24 coupled to a backplane 42 to form an exemplary portion of generation system 26. In the preferred embodiment of FIG. 11, backplane is made up of a printed circuit board 44 having a plurality of backplane connectors 46. In use, board connector 40 of one PC thermopile 24 is connected to each backplane connector

46. Backplane 42 contains traces (not shown) interconnecting PC thermopiles 24.

[0065] Those skilled in the art will appreciate that FIG. 11 is also highly simplified for clarity. In practice, backplane 42 may be one of a plurality of backplanes 42 interconnected to provide the desired thermoarray *TA*. For example, to produce the previously discussed array of 40,000 × 50 thermocouples *TC* when each PC thermopile 24 contains 1000 thermocouples *TC*, 50 backplanes 42 may be connected in parallel, where each backplane 42 has 40 backplane connectors 46 connected in series. This would allow each backplane connector 46 to be connected to one of 2000 PC thermopile 24, and would produce the desired array of 2,000,000 series/parallel thermocouples *TC*.

[0066] Those skilled in the art will appreciate that arrangements of thermocouples *TC* and PC thermopiles 24 other than those exemplified hereinbefore for the preferred embodiments may be realized without departing from the spirit of the present invention.

[0067] In FIGs. 10 and 11, connectors 40 and 46 are depicted as conventional PC edge-card connectors. Those skilled in the art will appreciate that this is exemplary only and that no specific connector type is required by the present invention. The use of other connector types does not depart from the spirit of the present invention.

[0068] FIGs. 12 through 15 show cross-sectional views of PC thermopile 24 taken at line 12-12 of FIG. 10 in accordance with alternative embodiments of the present invention. The following discussion refers to FIGs. 10 through 15.

[0069] FIG. 12 demonstrates the use of a plated-through hole and an overlap to form a physical junction 48 (i.e., either junction J_1 or J_2). In this embodiment, a hole 50 is made through substrate 30 at the desired location of each physical junction 48 (i.e., at the location of each junction J_1 and J_2). Each hole 50

is then plated with copper, thereby making each hole 50 a copper plated-through hole 52 that extends from first surface 32 to second surface 36. Copper traces 28, including copper pads 54, are then etched or deposited upon first surface 32 of substrate 30, while only copper pads 54 are etched or deposited upon second surface 36. Opposing copper pads 54 conductively combine with plated-through holes 52 to form couplings 38. Couplings 38 extend copper traces 28 from first surface 32 to second surface 36 of substrate 30. Constantan traces 34 are then deposited upon second surface 36 of substrate 30. Physical junctions 48 are formed at couplings 38 wherever constantan traces 34 come into contact with copper pads 54 upon second surface 36.

[0070] FIG. 13 demonstrates the use of a filled plated-through hole to form physical junction 48. In this embodiment, hole 50 is again made through substrate 30 and plated with copper to form a copper plated-through hole 52 extending from first surface 32 to second surface 36 at the desired location of each physical junction 48. Copper traces 28, including copper pads 54, are etched or deposited only upon first surface 32 of substrate 30. Constantan traces 34, including constantan pads 56, are etched or deposited upon second surface 36. Copper pads 54, plated-through holes 52, and constantan pads 56 together form couplings 38. Physical junctions 48 are formed within couplings 38 wherever constantan pads 56 come into contact with copper plated-through holes 52 at second surface 36.

[0071] Copper pads 54 on first surface 32 conductively combine with plated through holes 52. This is not necessarily the case with constantan pads 56, which may form weak electrical bonds with copper plated-through holes 52. This problem may be eliminated by filling plated-through holes with a connection conductor 58 (typically solder), which does form a strong electrical bond with both copper and constantan.

[0072] FIG. 14 demonstrates the use of a pin to form physical junction. In this embodiment, hole 50 is made through

substrate 30, but not plated. Copper traces 28, including copper pads 54, are etched or deposited upon first surface 32 of substrate 30, and constantan traces 34, including constantan pads 56, are etched or deposited upon second surface 36. A pin 60 is passed through each hole 50 and electromechanically affixed to copper pads 54 upon first surface 32 and constantan pads 56 upon second surface 36 (typically by soldering). Pins 60 are formed of a pin conductor 62 (typically copper). Copper pads 54, pins 60, and constantan pads 56 together form couplings 38. Physical junctions 48 are formed wherever pins 60 come into contact with constantan pads 56.

[0073] FIG. 15 demonstrates the use of a pin incorporating a heat sink to form physical junction. This embodiment is substantially identical to the embodiment of FIG. 14 (discussed hereinbefore) save that pin 60 is extended and flared upon on side to form a heat sink 64. Heat sink 64 serves to better maintain the temperature of physical junction 48 at the temperature of the surrounding medium (discussed hereinafter). Those skilled in the art will appreciate that the shape of heat sink 64 is irrelevant to this discussion. The use of any given shape does not depart from the spirit of the present invention.

[0074] The following discussion refers to FIGs. 4, 8, 10 and 11.

[0075] In order for PC thermopile 24 to produce electricity, the junctions J_1 and J_2 of each thermocouple TC must be at different temperatures. On PC thermopile 24, junctions J_1 and J_2 are realized as physical junctions 48 located substantially at couplings 38. Physical junctions 48 are divided into a first junction group 66 containing all junctions J_1 and a second junction group 68 containing all junctions J_2. First junction group 66 is located on a first thermal portion 70 of substrate 30. Similarly, second junction group 68 is located on a second thermal portion 72 of substrate 30.

[0076] During operation, first thermal portion 70 (i.e., all junctions J_1) is maintained at temperature T_1 (e.g., 0°C), and second thermal portion 72 (i.e., all junctions J_2) is maintained at temperature T_2 (e.g., 100°C). In this manner, each thermocouple TC produces voltage E_{TC} at current I_{TC}, which together produce voltage E_{TP} at current I_{TP} as an output of PC thermopile 24.

[0077] In the preferred embodiment, all junctions J_1 in first thermal portion 70 are maintained at temperature T_1 by surrounding first thermal portion 70 of each PC thermopile 24 with a gas bath 74. The arrangement of PC thermopiles 24 in generation system 26 is desirably such that gas bath 74 may be a flow of nonconductive gas (e.g., air). gas bath 74 would therefore be able to cool (i.e., remove heat from) junctions J_1 and maintain a stable temperature T_1 thereat. The use of pins 60 (FIGs. 14 and 15) at junctions J_1 increases the mass of junctions J_1, thereby improving thermal stability. The use of heat sinks 64 on pins 60 (FIG. 15) further increases mass and significantly improves heat transfer.

[0078] Similarly, in the preferred embodiment, all junctions J_2 in second thermal portion 72 are maintained at temperature T_2 by surrounding second thermal portion 72 of each PC thermopile 24 with a liquid bath 76. The arrangement of PC thermopiles 24 in generation system 26 is desirably such that liquid bath 76 may be a flow of heated nonconductive liquid (e.g., oil). Liquid bath 76 would therefore be able to heat (i.e., pass heat into) junctions J_2 and maintain a stable temperature T_2 thereat. Again, the use of pins 60 at junctions J_2 increases the mass of junctions J_2 and improves thermal stability. The use of heat sinks 64 on pins 60 further increases mass and significantly improves heat transfer.

[0079] Those skilled in the art will appreciate that while the preferred embodiment uses gas bath 74 and liquid bath 76, this is not a requirement of the present invention. For example, two gas baths 74 at dissimilar temperatures may be used without departing from the spirit of the present invention.

[0080] Gas bath 74 and liquid bath 76 are separated by an insulator 78. Insulator 78 is desirably designed to surround each PC thermopile 24 and thermally isolate first and second portions 70 and 72.

[0081] In the preferred embodiment, liquid bath 76 is hotter than gas bath 74. This is not a requirement of the present invention, and gas and liquid baths 74 and 76 may be any desired temperatures without departing from the spirit of the present invention. For example, gas bath could be 150°C and liquid bath could be 0°C if those temperatures of gas and liquid are available.

[0082] Since the entirety of thermoelectric generation system 26 has no moving parts, functional life expectancy becomes essentially the life expectancy of the material used. With proper material selection, this could be decades.

[0083] Throughout this discussion it was assumed that the materials used for thermocouples TC were copper and constantan. These materials were desirable for their stability, resistance to progressive corrosion, and low cost. It will be appreciated that other materials may be desirable when other factors are considered. For example, if the requisite heat is available only in a corrosive environment, then platinum and platinum/rubidium may be desirable for thermocouples TC.

[0084] Also throughout this discussion, temperatures T_1 and T_2 were assumed to be 0°C and 100°C, respectively (i.e., the freezing and boiling points of water). This assumption was made for convenience only, and any two dissimilar temperatures may be used. It will be appreciated that the greater the difference

between temperatures T_1 and T_2, the more efficient generation system 26 will become. Also, it will be appreciated that the "cold" temperature T_1 need not be cold in the literal sense, but only colder than temperature T_2. For example, generation system 26 would operate quite well were temperature T_1 to be 100°C and temperature T_2 to be 350°C. Naturally, proper selection of all materials (e.g., the composition of substrate 30) for the intended temperatures T_1 and T_2 would be required.

[0085] In summary, the present invention teaches a thermoelectric generation system 26 utilizing PC thermopiles 24. Though the use of PC thermopiles 24, otherwise-wasted heat derived from a natural or artificial process may be used to generate significant amounts of electrical energy. The result is a non-polluting energy source that is immune to diurnal, climatological, and meteorological effects, has no moving parts, and is readily adaptable to variant energy needs.

[0086] Although the preferred embodiments of the invention have been illustrated and described in detail, it will be readily apparent to those skilled in the art that various modifications may be made therein without departing from the spirit of the invention or from the scope of the appended claims.